

# Z+Jets at the Tevatron



Gavin Hesketh,  
Northeastern University

31<sup>st</sup> July  
ICHEP '08



**Motivation**

**Z  $p_T$  Measurement**

**Z + Jet Measurements**

## W and Z production as probes of QCD:

- production dynamics of massive bosons
- leptonic ( $e, \mu$ ) decay modes:
  - colourless, low backgrounds

## Most bosons produced at low $p_T$ :

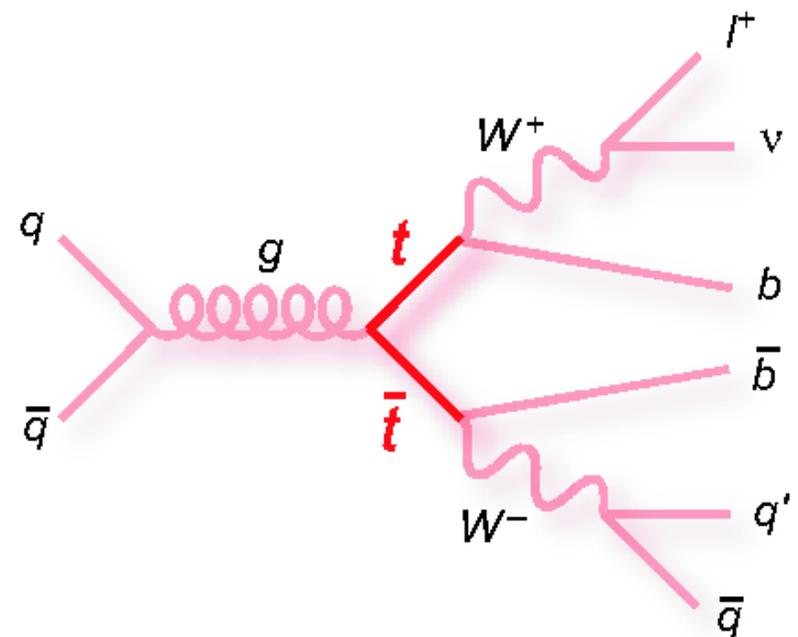
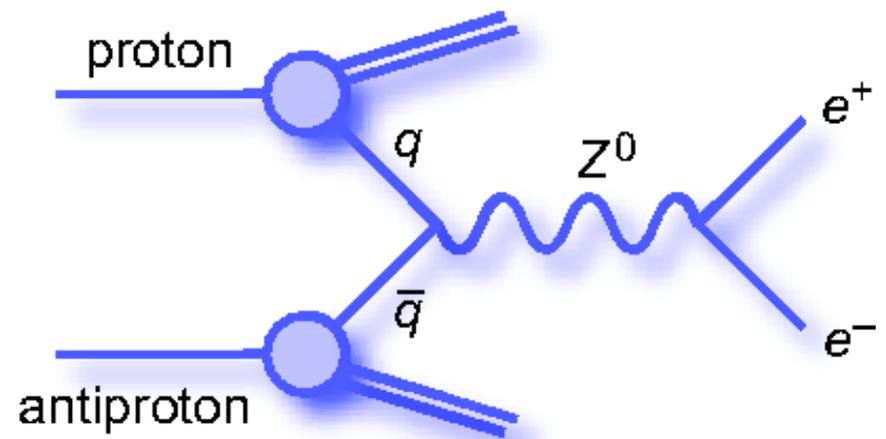
- recoil against soft gluons
- important for W mass measurement

## Boson + jet(s) production:

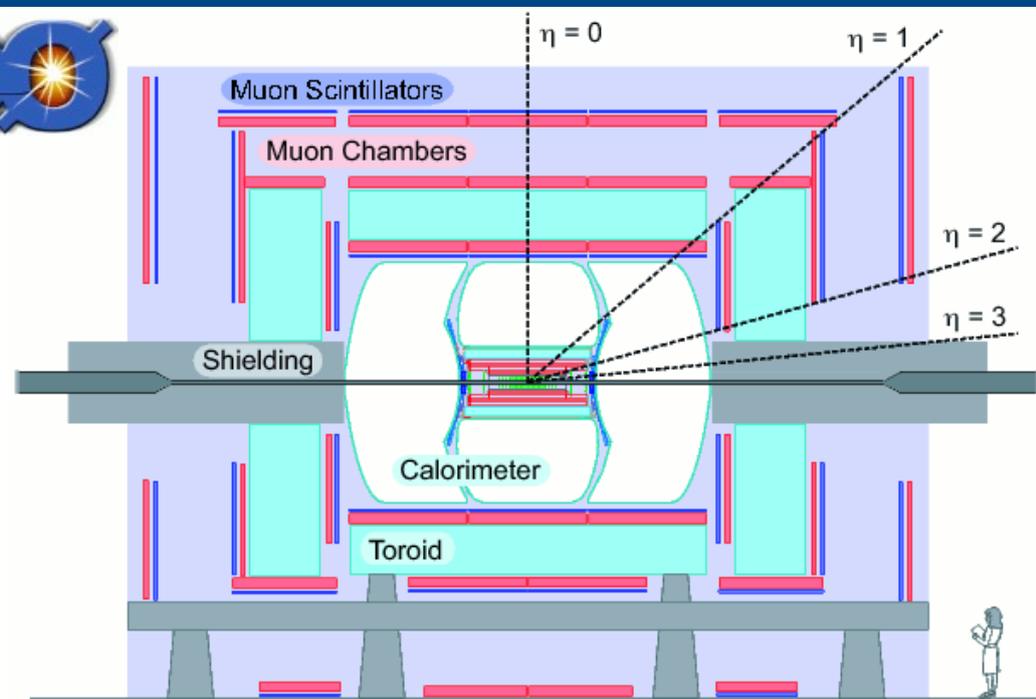
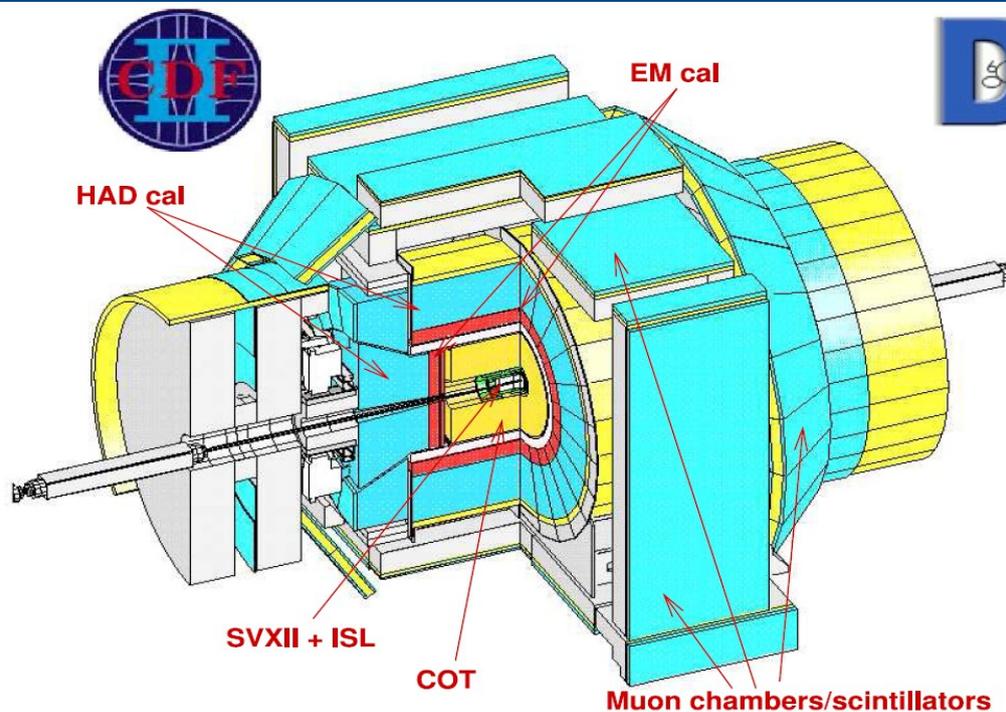
- smaller cross sections, but still larger than:
  - top, WH, ZH, SUSY
  - which have similar final states

## Experimental aims:

- measure differential cross sections
  - inclusive boson
  - and boson + jet production

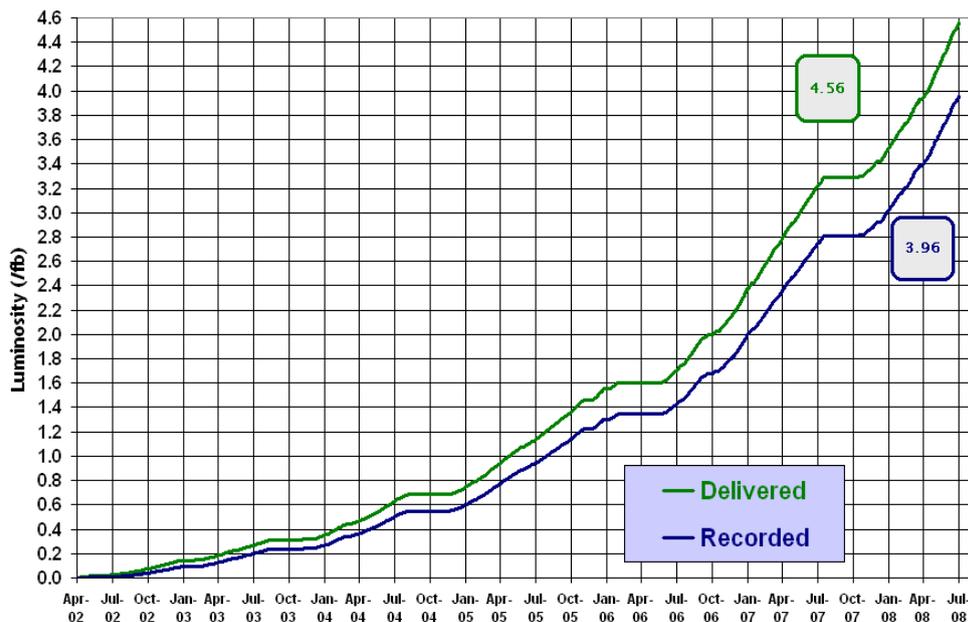


# The Experiments



Run II Integrated Luminosity

19 April 2002 - 20 July 2008



**Experiments have  $\sim 4 \text{ fb}^{-1}$  on tape**

- results today using  $1 - 2.5 \text{ fb}^{-1}$

**Cross sections at Tevatron:**

-  $W \rightarrow l\nu$ :  $2687 \pm 53 \text{ pb}$

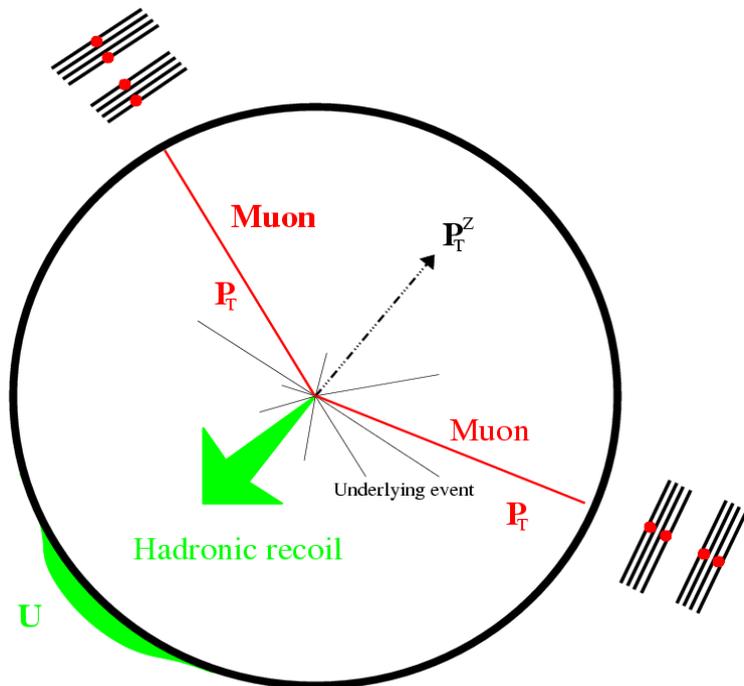
NNLO prediction

-  $Z \rightarrow ll$ :  $251 \pm 5 \text{ pb}$

Van Neerven *et al*

→ millions of W's; 100's k Z's per  $\text{fb}^{-1}$   
 ~ 20 % of events contain  $\geq 1$  jet

# Reconstructing Z + Jets

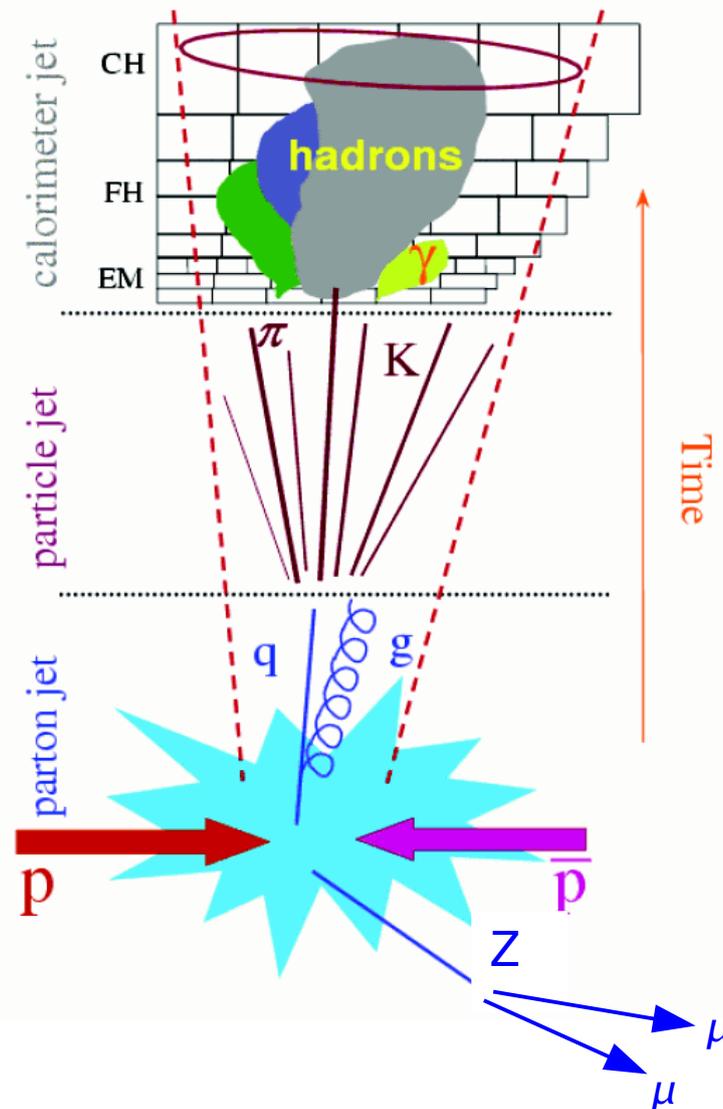


## Z is a clean signal:

- require two high  $p_T$  leptons
  - >25 GeV (e), >15 GeV ( $\mu$ )
- cover wide rapidity range:
  - $|\eta| < \sim 3.2$  (e),  $|\eta| < \sim 2$  ( $\mu$ )
- trigger on either (or both)
- **backgrounds low** (< 2 - 3 %):
  - jets “faking” electrons
  - semi-leptonic decays
  - di-boson production

## Use a mid-point cone jet algorithm

- cone size used here: 0.5 (D0), 0.7 (CDF)
- small differences in the algorithms





# Z p<sub>T</sub> Measurement

## Low Z p<sub>T</sub> caused mainly by soft gluon emission

- Z p<sub>T</sub> < ~30 GeV

→ gluon re-summation, eg within CSS formalism

- BLNY parameterisation:

$$S_{NP}(b, Q^2) = [g_1 + g_2 \ln(\frac{Q}{2Q_0}) + g_1 g_3 \ln(100x_i x_j)] b^2$$

- Implemented in RESBOS Monte Carlo.

- “small-x broadening” of Z p<sub>T</sub>:

- requires modified parameterisation at low x

- typical  $\langle x \rangle = M_Z / \sqrt{s} = 0.046$

- For  $2 < |y_Z| < 3$ ,  $\langle x \rangle$  between 0.002 and 0.006.

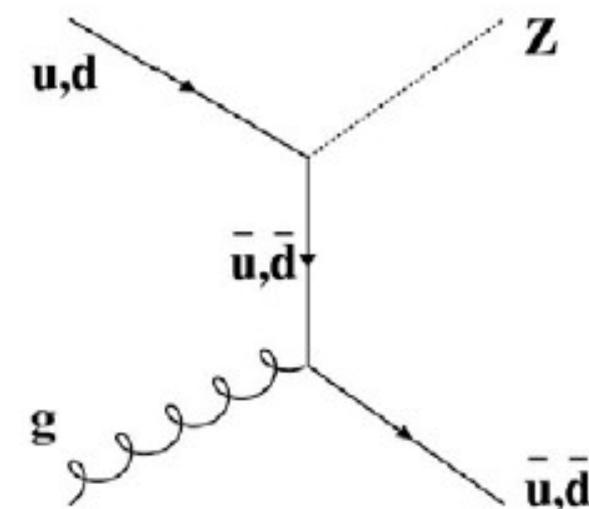
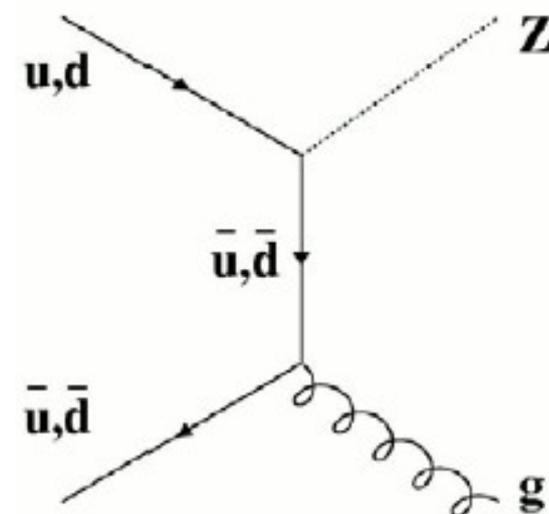
## High Z p<sub>T</sub> dominated by hard parton emission

- Z p<sub>T</sub> > ~ 50 GeV

→ perturbative QCD

- NLO prediction in RESBOS

- NNLO prediction from Melnikov, Petriello





# Z p<sub>T</sub> Result

## Result using 0.98 fb<sup>-1</sup>, Z → ee channel:

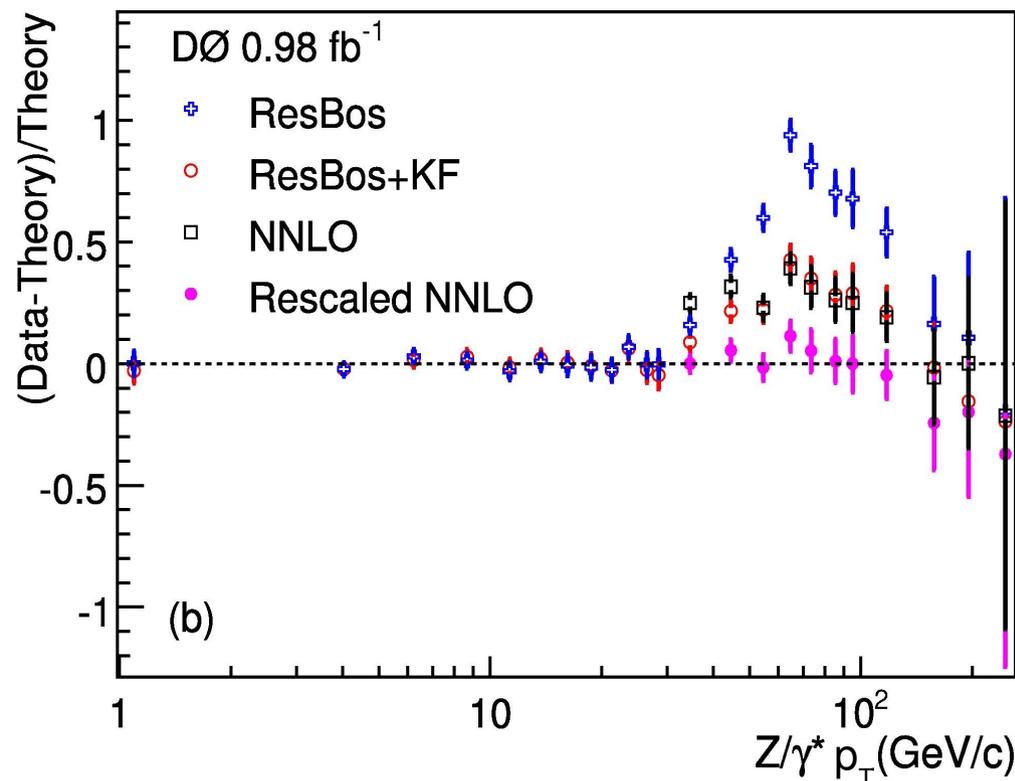
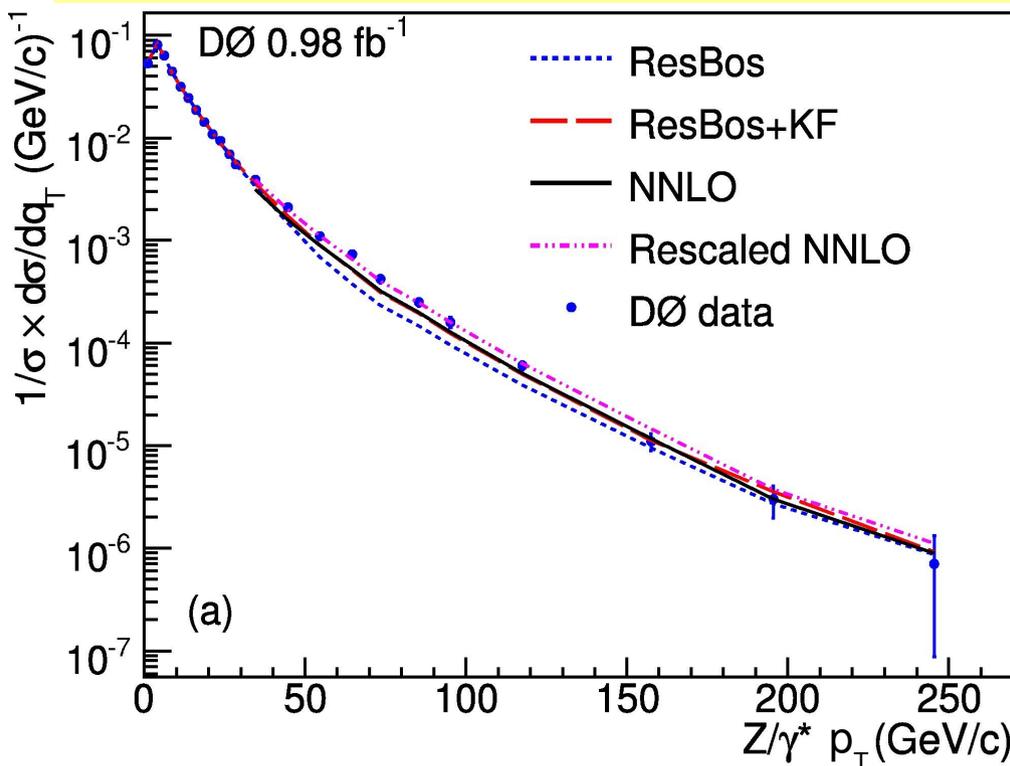
- differential cross section over wide Z p<sub>T</sub> range: < 260 GeV

- normalise: 1/σ × dσ / dp<sub>T</sub>

- test RESBOS modeling at low Z p<sub>T</sub>

- test perturbative prediction at high Z p<sub>T</sub>

→ describes shape well, but a scale factor (1.25) is needed to correct normalisation





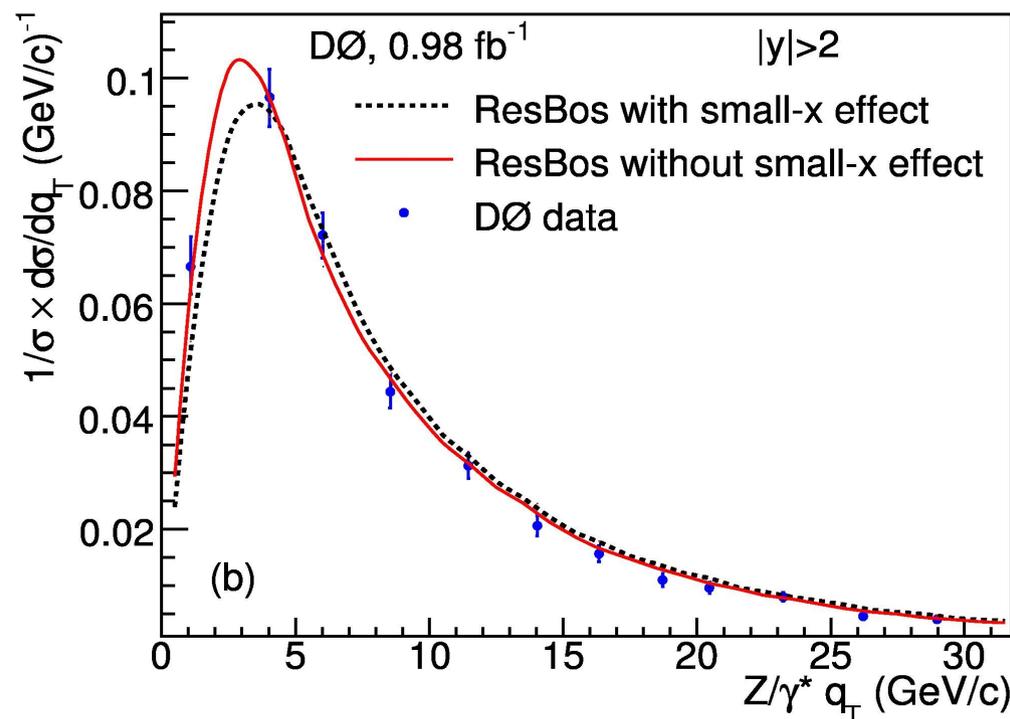
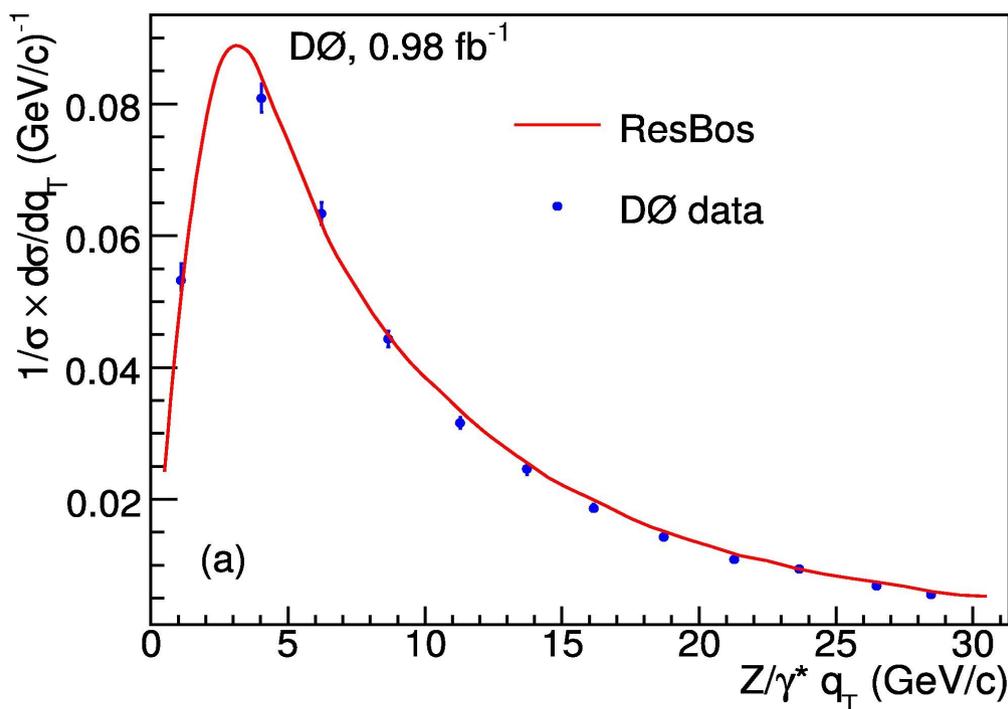
$$Z p_T \rightarrow g_2$$

### Focus on low $p_T$ :

- RESBOS describes data well
- extract  $g_2 = 0.77 \pm 0.06$  (current world average =  $0.68^{+0.02}_{-0.01}$ )
- limited by experimental resolution.

### First test of small-x broadening using high rapidity Zs!

- Data prefer calculation without small x effect.



PRL 100, 102002 (2008)



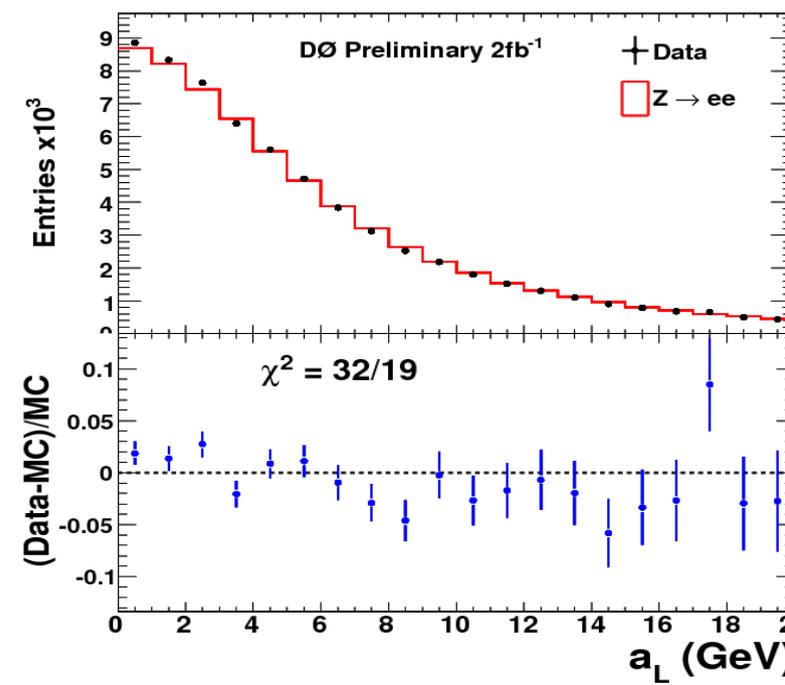
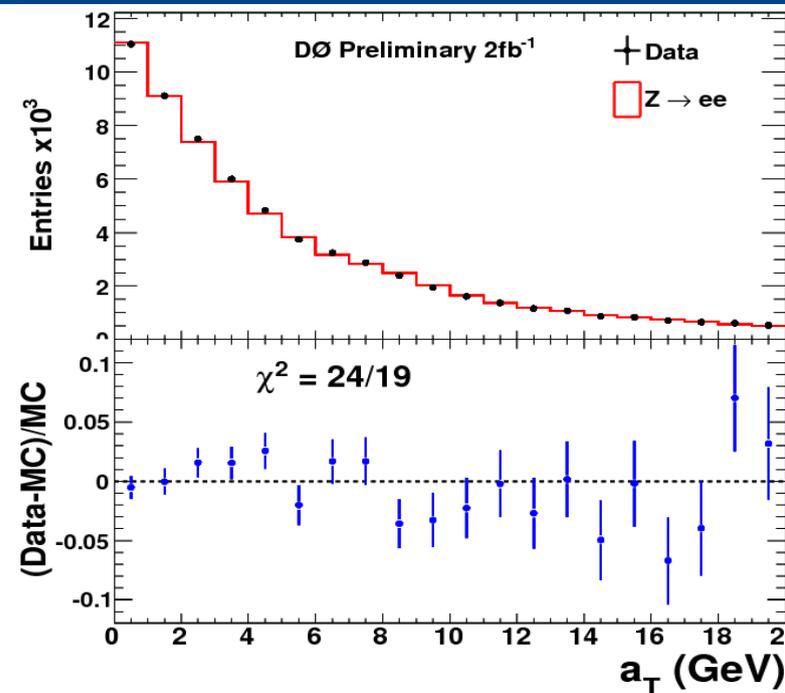
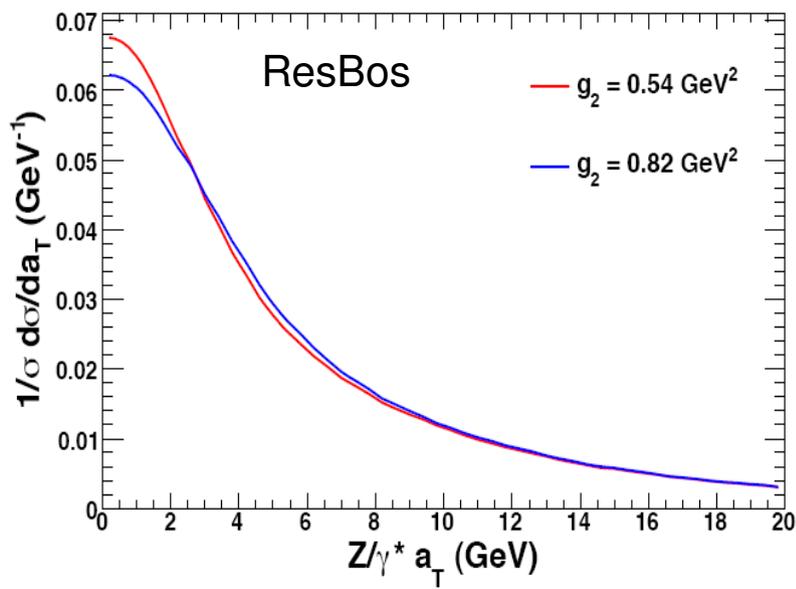
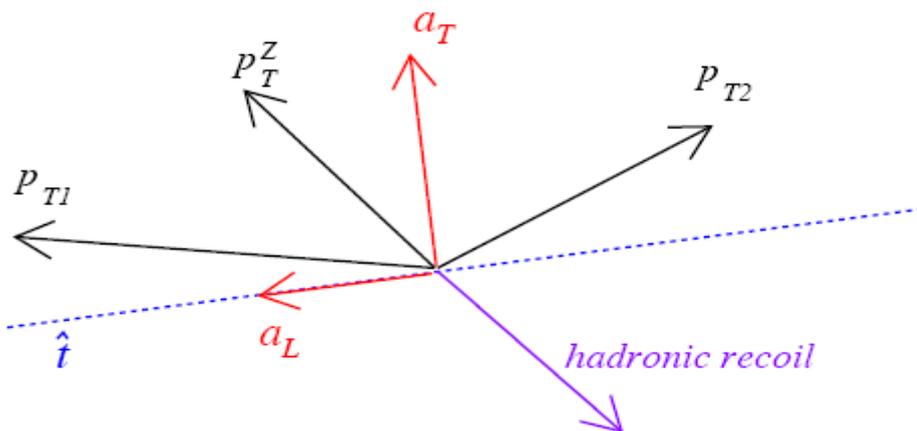
# New $Z p_T \rightarrow g_2$

## New DØ analysis:

- $2 \text{ fb}^{-1}$ , combining  $Z \rightarrow ee$  and  $Z \rightarrow \mu\mu$  channels

To increase sensitivity to  $g_2$ , define a new variable:

- $a_T$  largely insensitive to experimental resolution!





# New $g_2$ Result

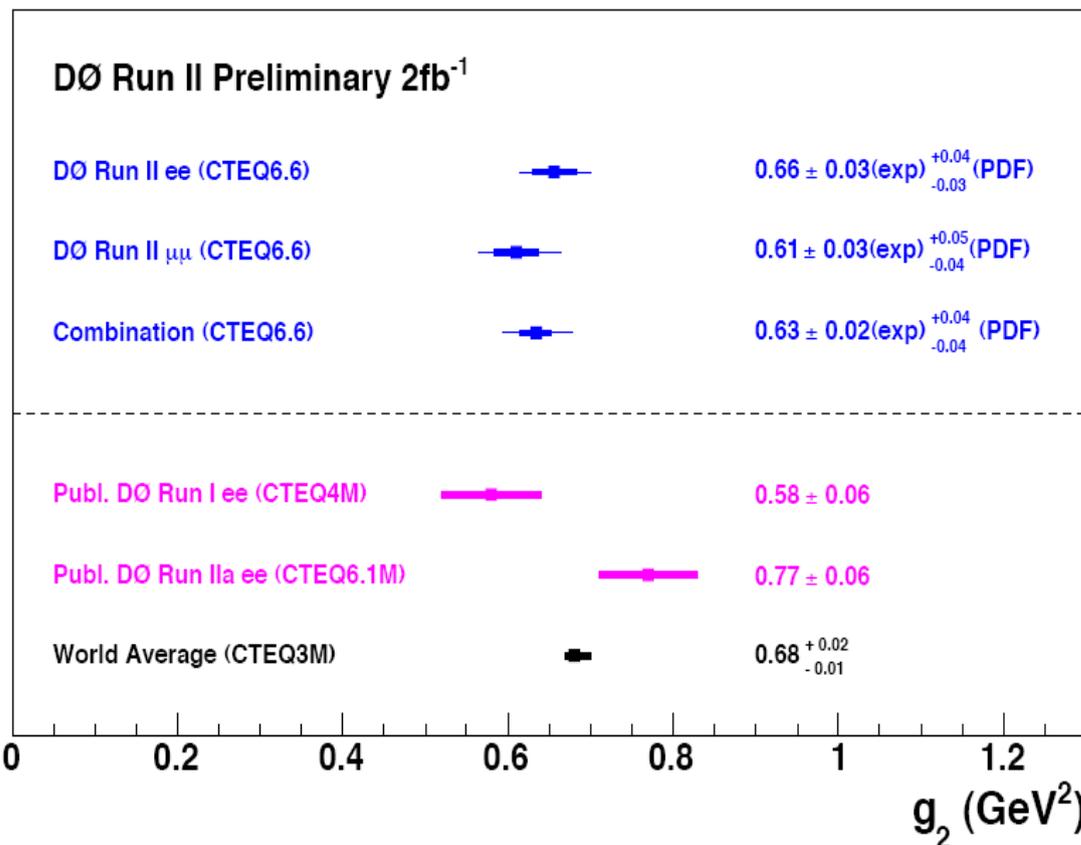
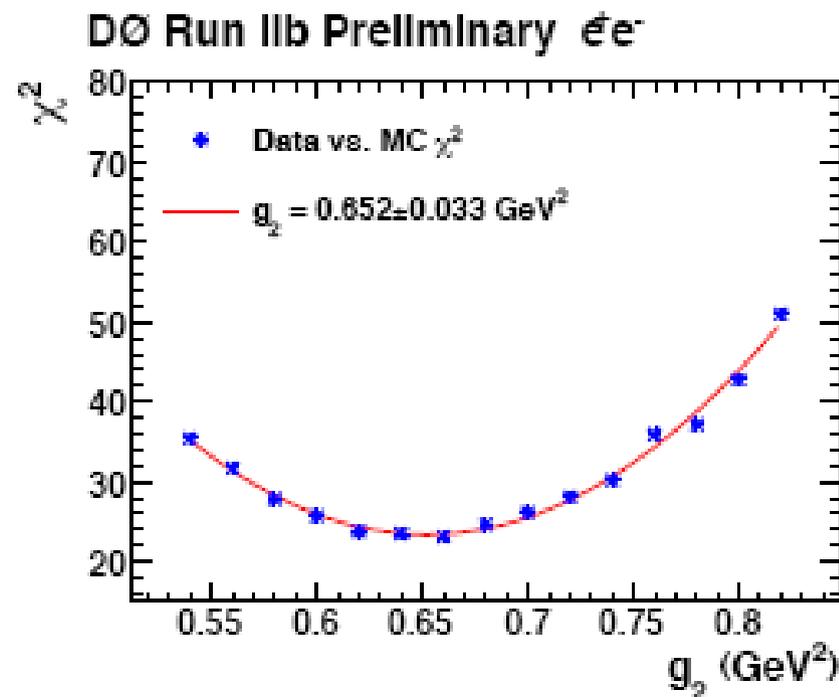
Data not unfolded for preliminary result.

### Extract $g_2$ by:

- generate RESBOS samples with various  $g_2$  values
- re-weight PYTHIA + full detector simulation
- fit re-weighted PYTHIA samples to data

### Statistics limited!

- ~4.5 % stat. uncertainty (largest syst. ~ 2 %)



### Result:

$$g_2 = 0.63 \pm 0.02 \text{ (exp.)} \pm 0.03 \text{ (PDF)}$$

Best single measurement, comparable accuracy to world average:  $0.68^{+0.02}_{-0.01}$

**W/Z + 3, 4... jets are a probe of QCD modeling.**

**Also dominate over many signals:**

- top, Higgs, SUSY
- will be much more common at LHC

**MCFM: NLO pQCD V +  $\leq 2$  partons**

**Current event generators:**

**Tree level matrix element + parton shower**

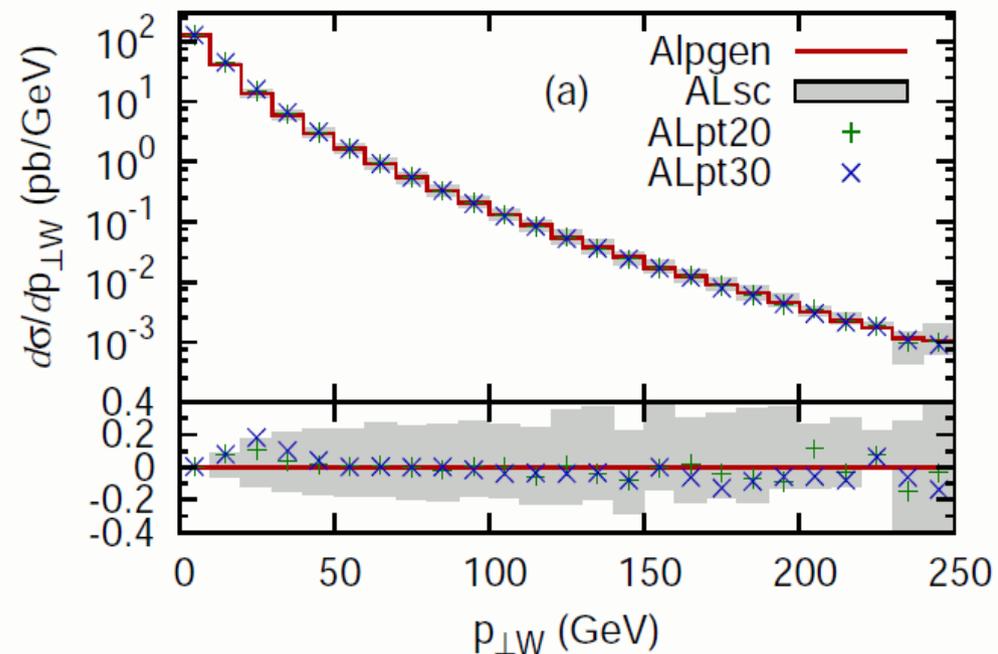
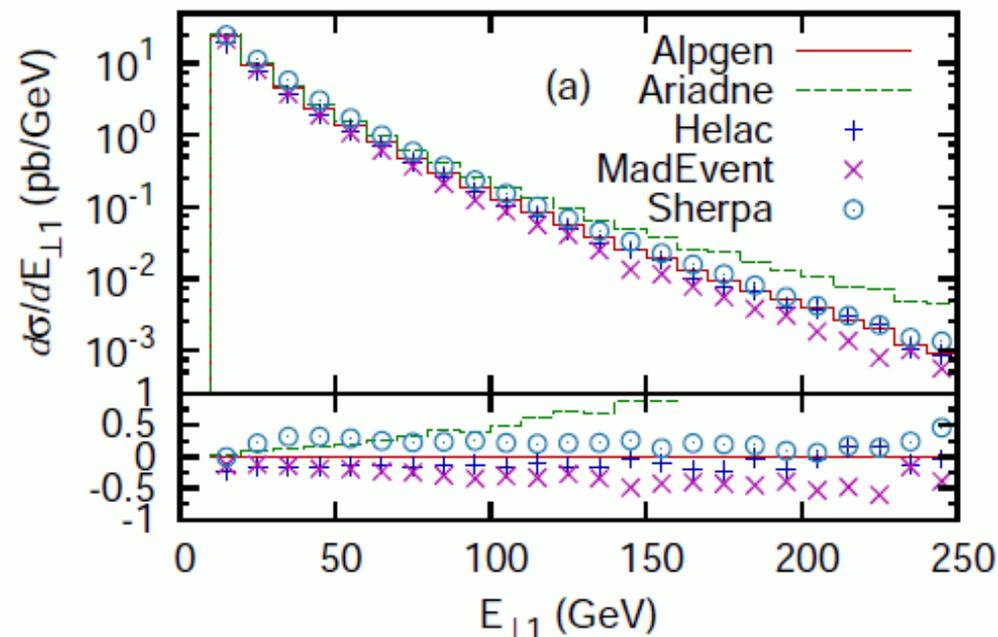
- matching schemes to avoid double counting
  - jets from ME and jets from PS
- MLM matching (Alpgen, MadEvent, Helac)
- CKKW scheme (Sherpa)
- Dipole Cascade (Ariadne)

**Contain (~untuned) internal parameters**

- see arXiv:0706.2569v1 [hep-ph]

**Alpgen is the main generator at CDF/D0**

- Pythia or Herwig used for showering



# Understanding Z + Jets

## Unfolding jet $p_T$ is difficult:

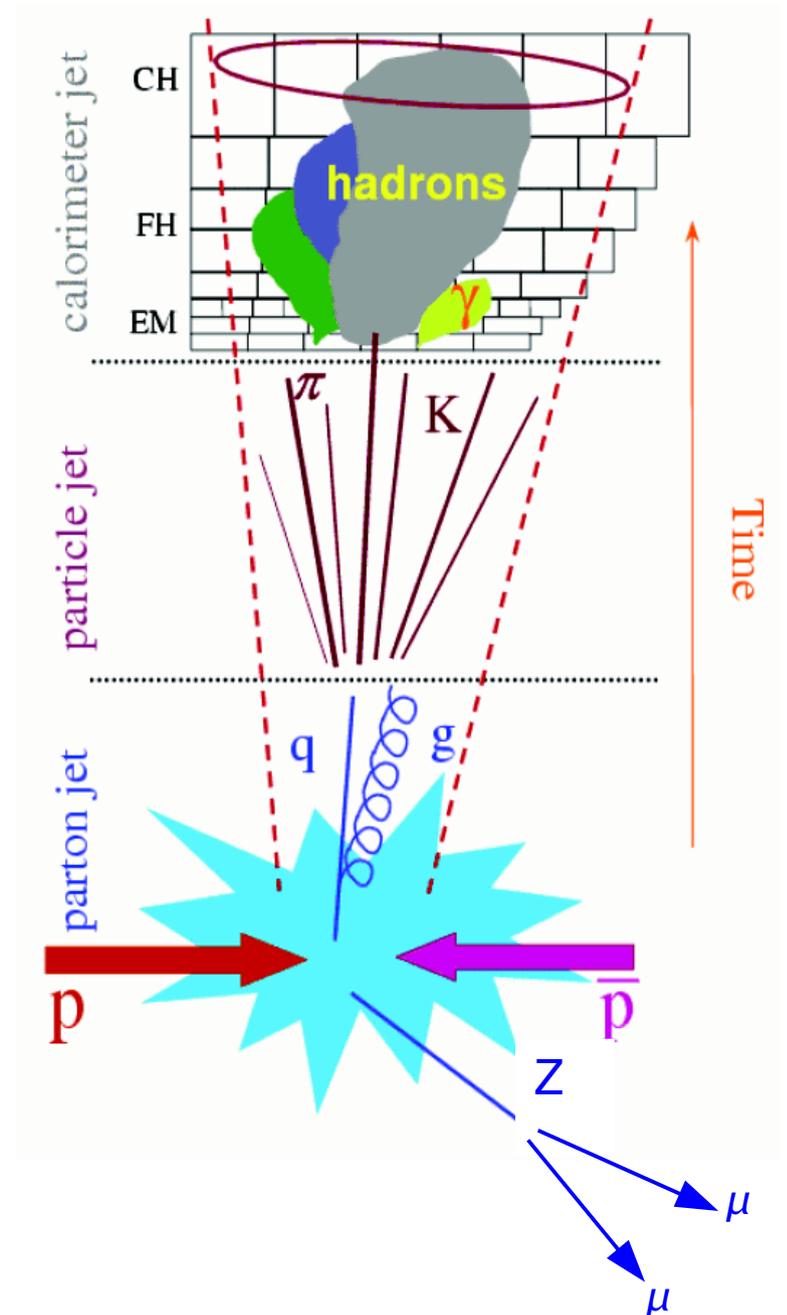
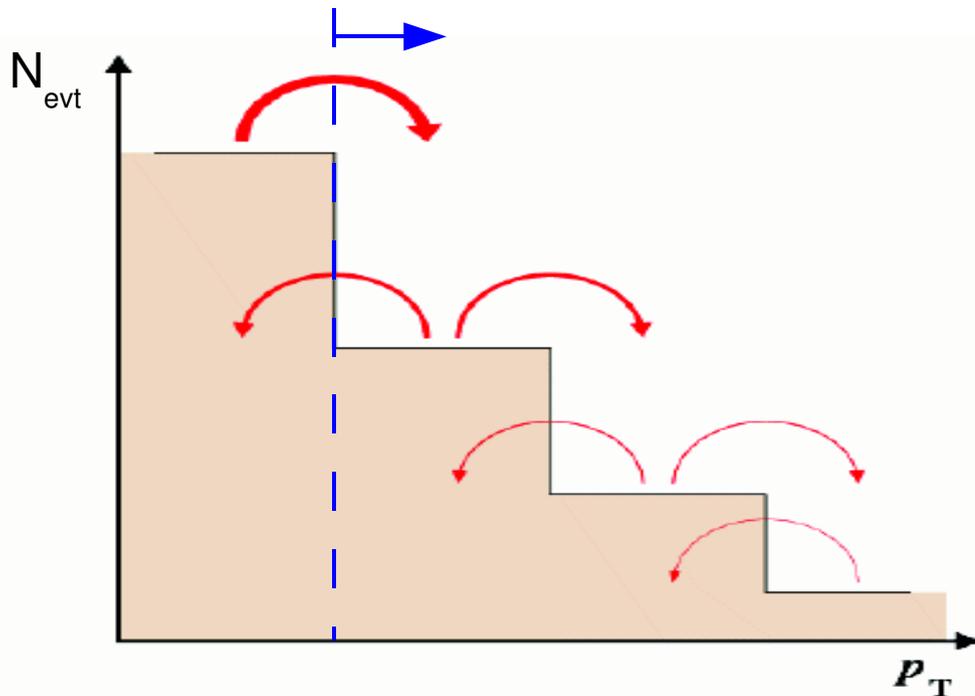
- finite experimental resolution
- steeply falling spectrum

## Excellent understanding of detector is vital:

- JES uncertainties dominate systematics

## Correct measurement to particle level:

- need corrections for MCFM NLO pQCD
  - non-perturbative effects
  - underlying event



## Update to CDF Z+jets analysis:

-  $Z \rightarrow ee$  channel, jet  $p_T > 30$ ,  $|y| < 2.1$

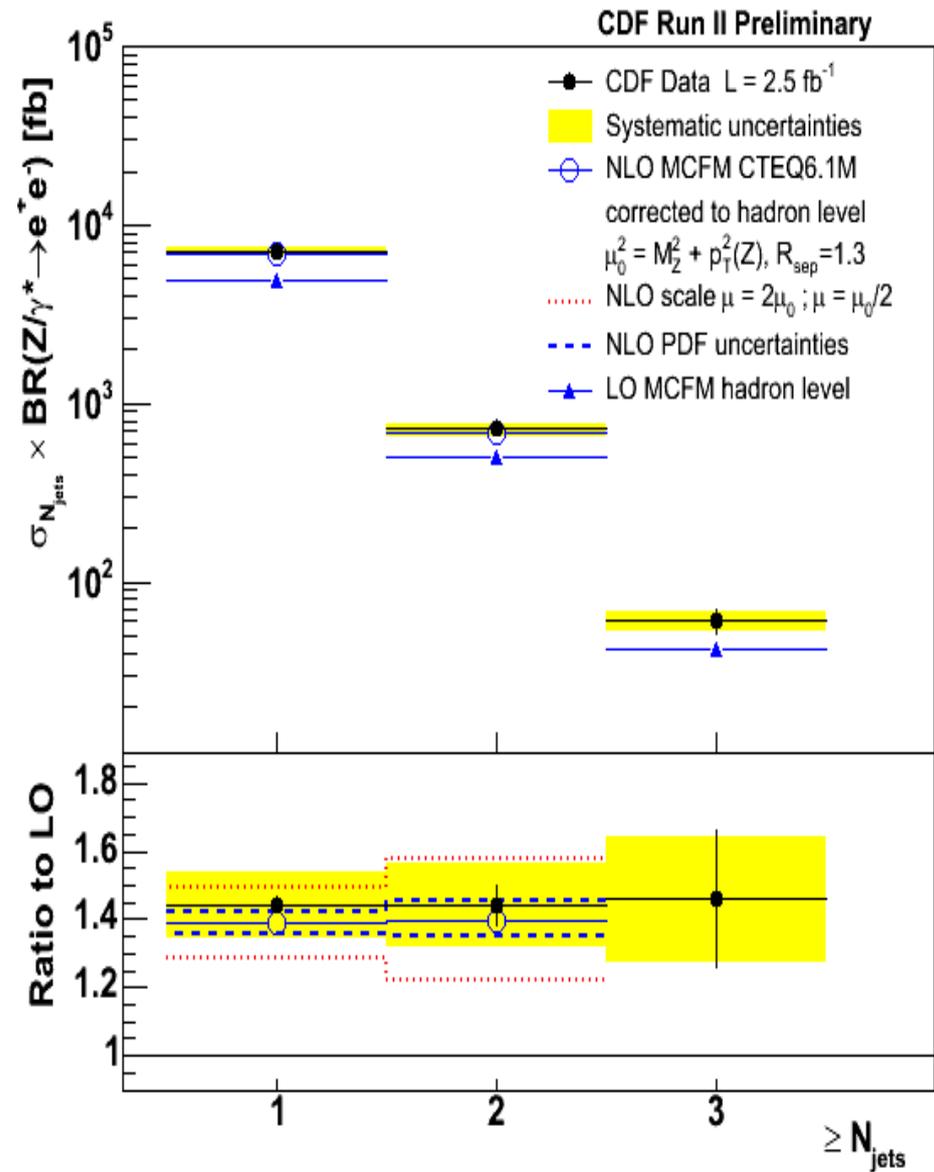
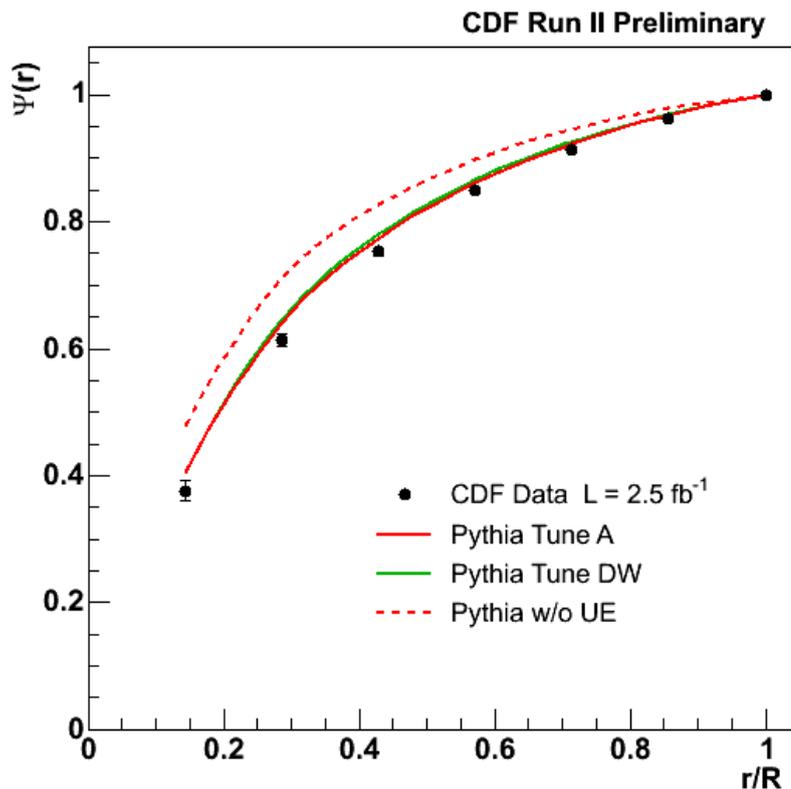
Published with  $1.7 \text{ fb}^{-1}$  PRL 100, 102001 (2008)

- updated with  $2.5 \text{ fb}^{-1}$

## Test detector modelling:

- eg, looking at jet shapes

## Measure cross section vs jet multiplicity



## Update to CDF Z+jets analysis:

-  $Z \rightarrow ee$  channel, jet  $p_T > 30$ ,  $|y| < 2.1$

Published with  $1.7 \text{ fb}^{-1}$  PRL 100, 102001 (2008)

- updated with  $2.5 \text{ fb}^{-1}$

## Differential cross sections in:

- inclusive jet  $p_T$ ,  $|y|$

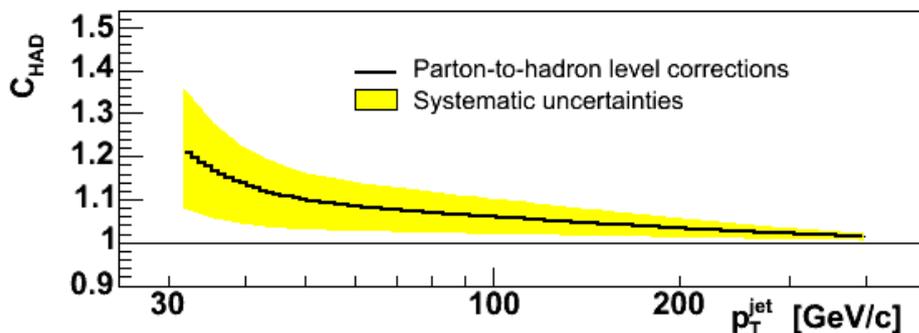
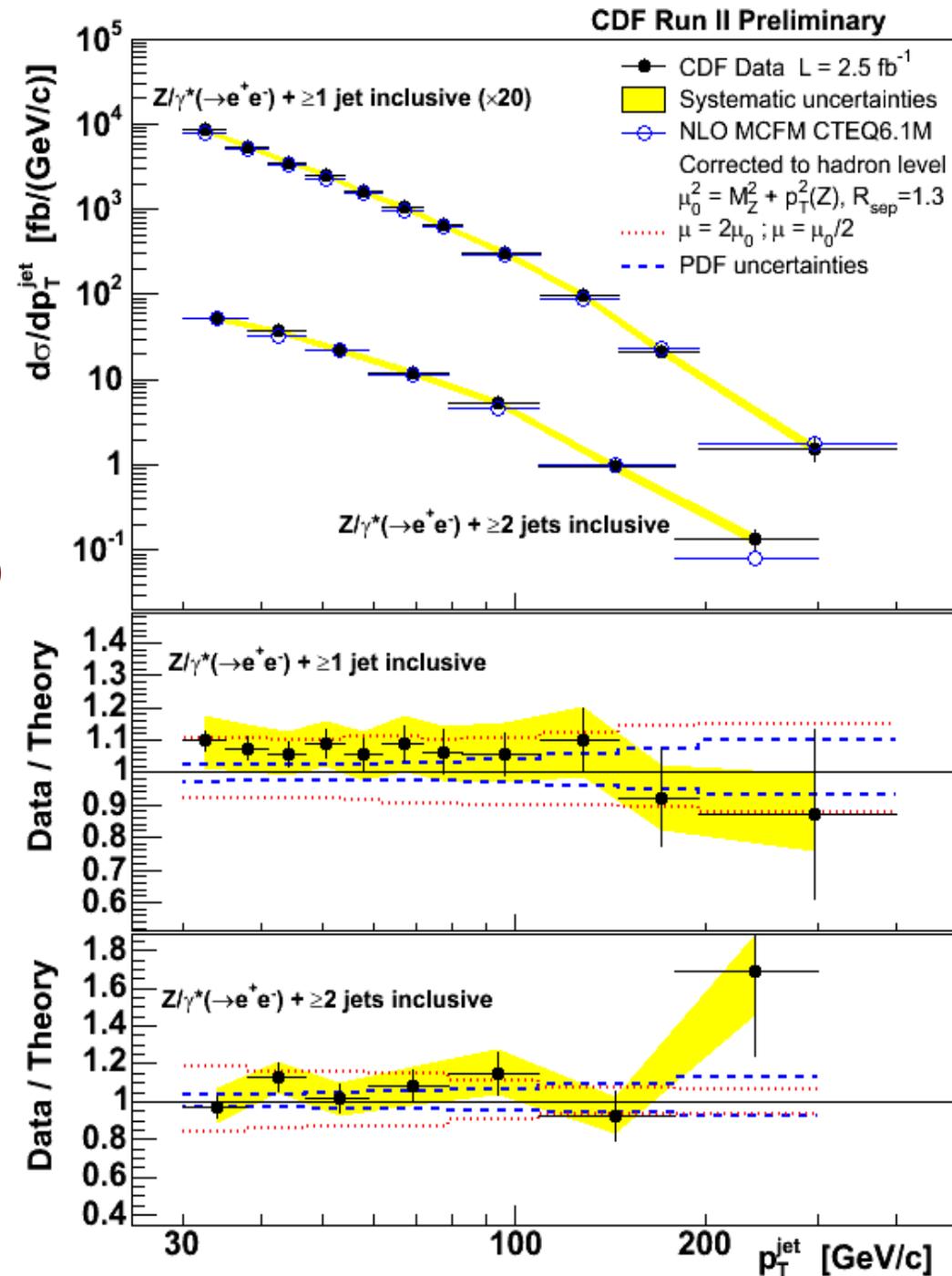
- improve result in high  $p_T$  tail.

## Compared to NLO pQCD prediction (MCFM)

- with corrections derived from Pythia

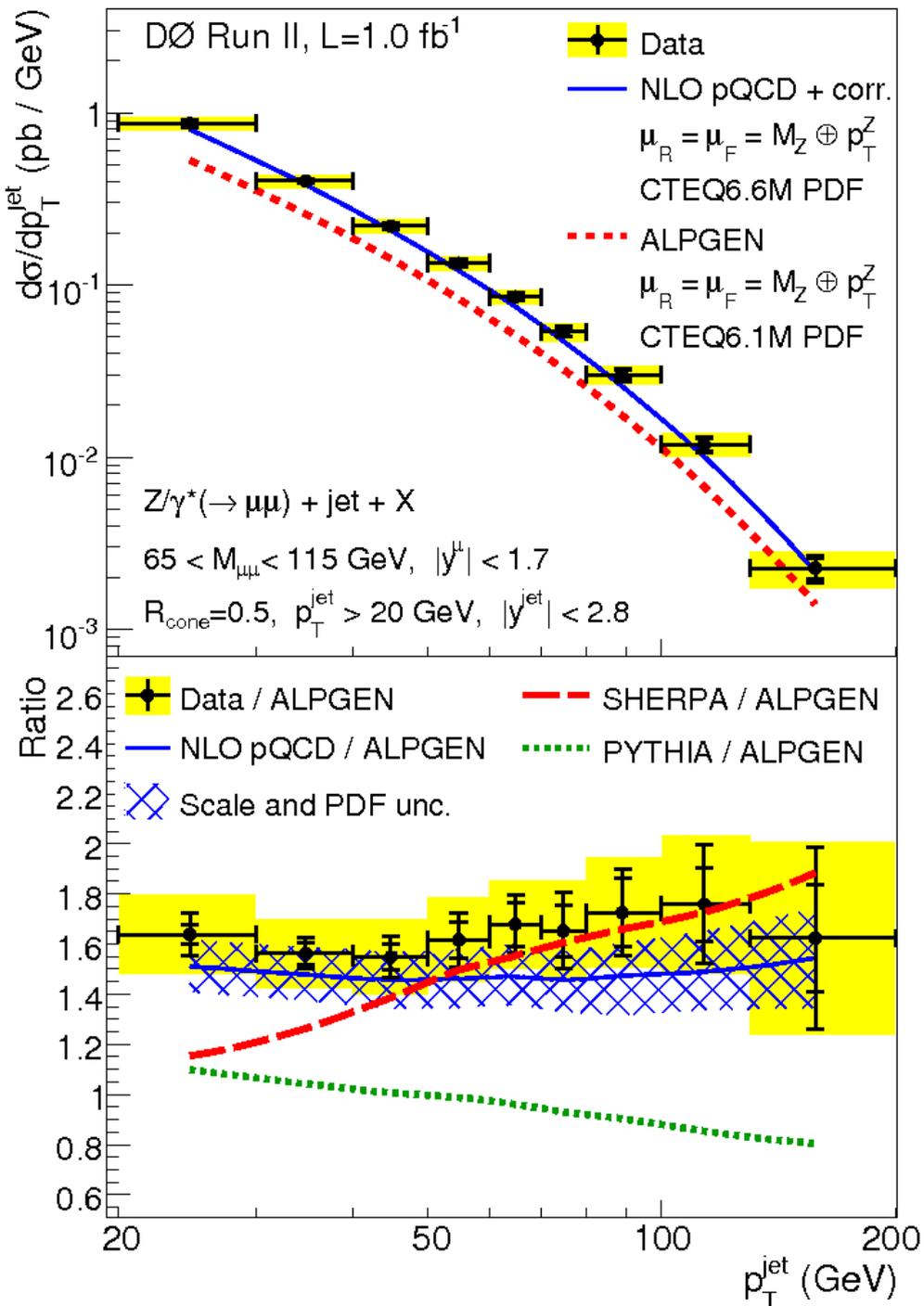
## Describes shapes well!

- normalisation agrees within uncertainties.





# New Z + $\geq 1$ Jet



## New D0 analysis of Z → μμ channel, 1 fb<sup>-1</sup>:

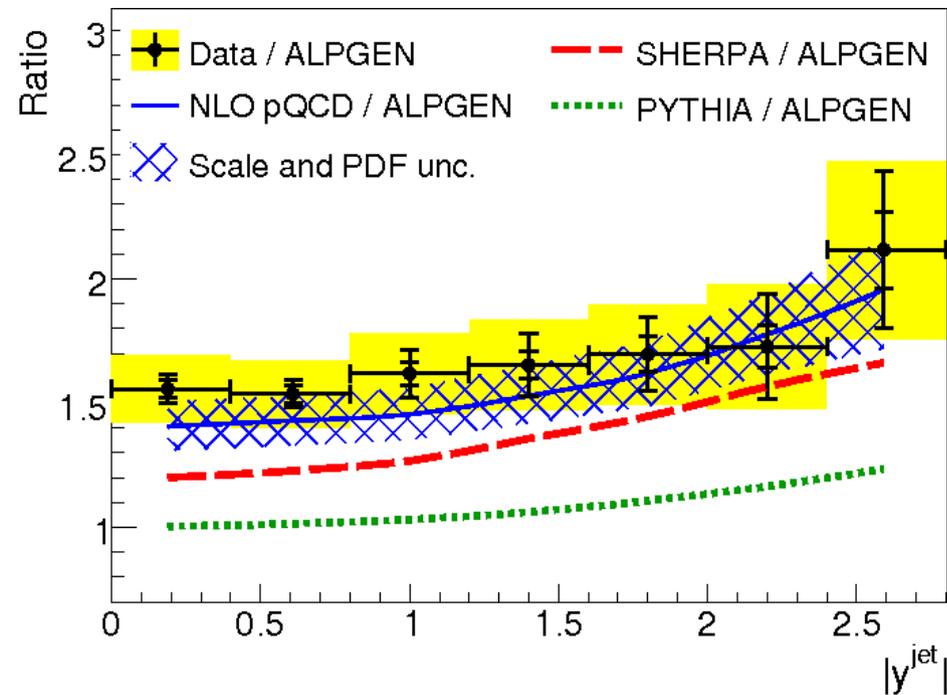
- jet p<sub>T</sub> > 20 GeV, jet |y| < 2.8, muon |y| < 1.7

### Differential cross sections in:

- leading jet p<sub>T</sub>, |y|; Z p<sub>T</sub>, |y|

### - comparisons to:

- NLO pQCD + corrections
- Alpgen (+Pythia showering)
- Sherpa
- Pythia





# New Z + $\geq 1$ Jet

## New D0 analysis of Z $\rightarrow \mu\mu$ channel, 1 fb<sup>-1</sup>:

- jet  $p_T > 20$  GeV, jet  $|y| < 2.8$ , muon  $|y| < 1.7$

## NLO describes shapes well

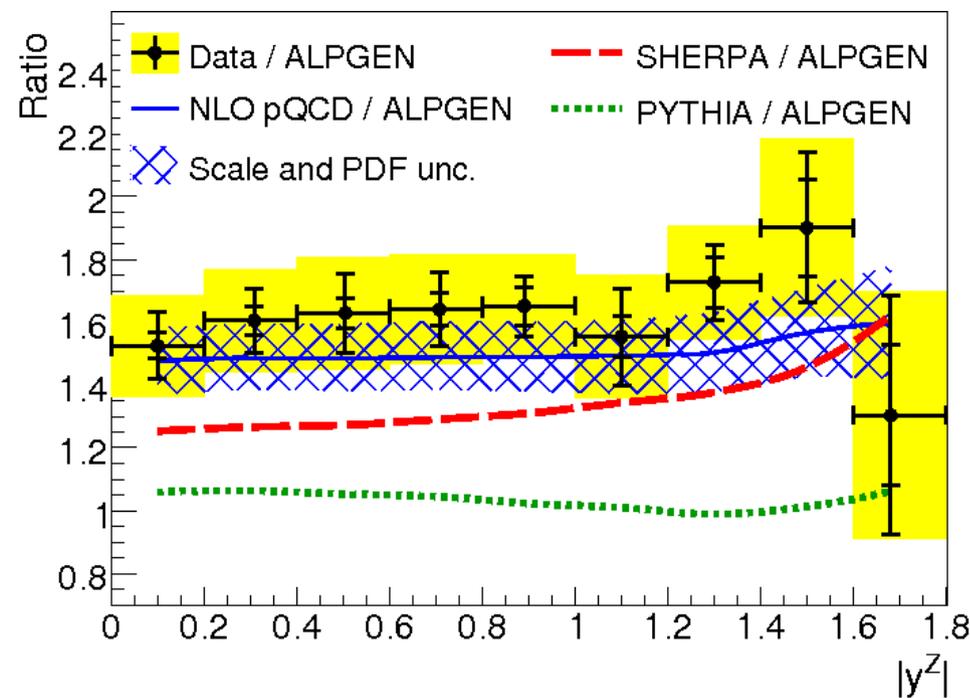
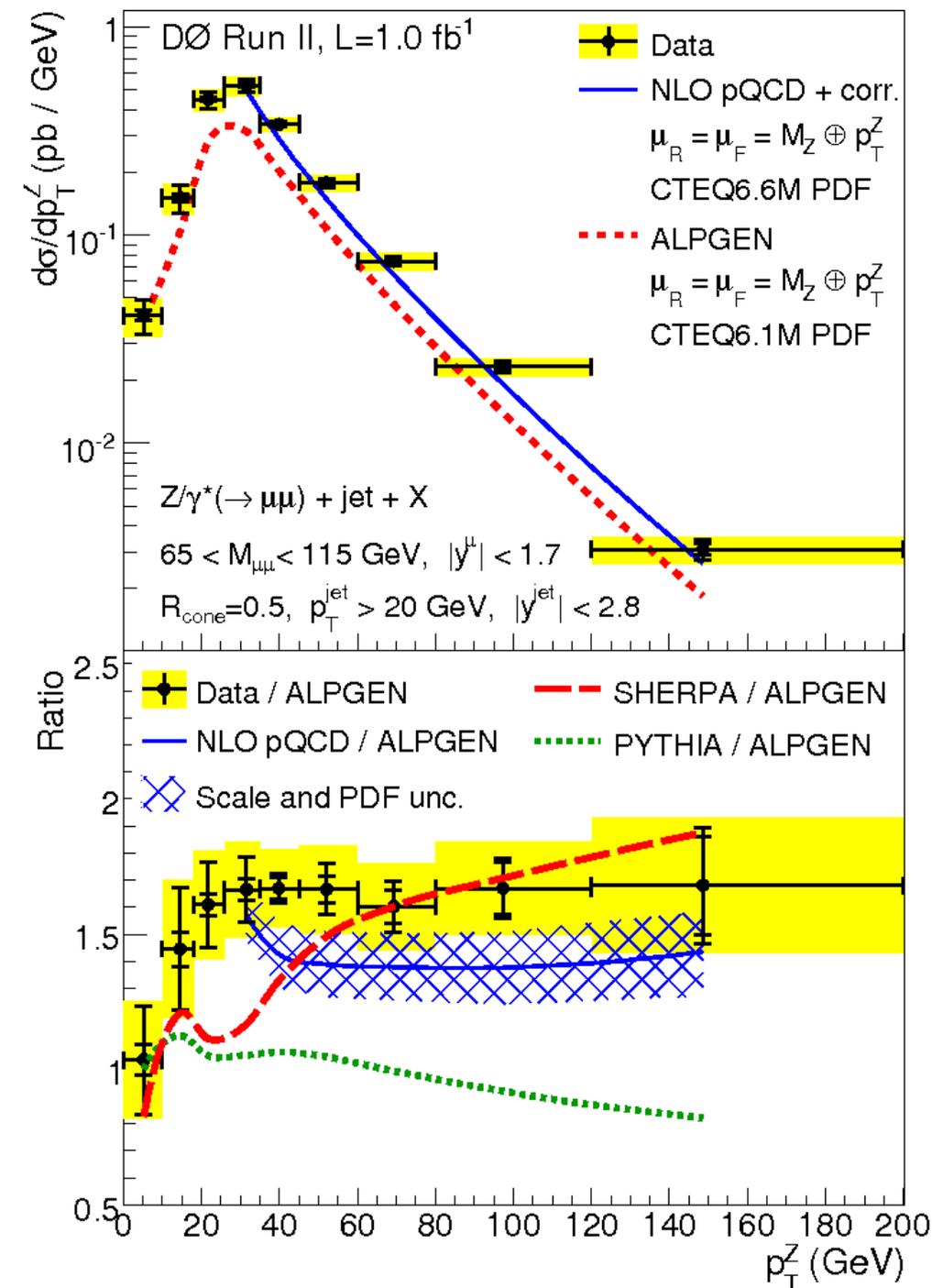
## Generators have varied success

- Alpgen performs reasonably well overall

## Low Z $p_T$ shows features:

- NLO dominated by non-perturbative corr.

- event generators may need tuning



## Z boson production as a probe of QCD at hadron colliders

### New measurement of non-perturbative form factor:

- $g_2 = 0.63 \pm 0.02$  (exp.)  $\pm 0.03$  (PDF)
- best single measurement, comparable accuracy to world average

### Measurements of differential cross sections in boson + jets:

- test NLO pQCD
- first comparisons to ME+PS generators
- important for many analyses at the Tevatron
  - and at the LHC

### Analysing more luminosity:

- improve  $g_2$  measurement (currently statistics limited)
- push to higher jet  $p_T$
- push to higher jet multiplicities.



Relationship between measured and particle jets  
-> the jet energy scale.

$$E_{ptcl} = \frac{E_{cal} - \text{Offset}}{(F_{\eta} \cdot R) \cdot S} \cdot k_{bias}$$

**Offset:** energy leaking into the jet cone;

- noise, pile-up, multiple interactions
- depends on instantaneous luminosity
- 1-3 % correction for jets.

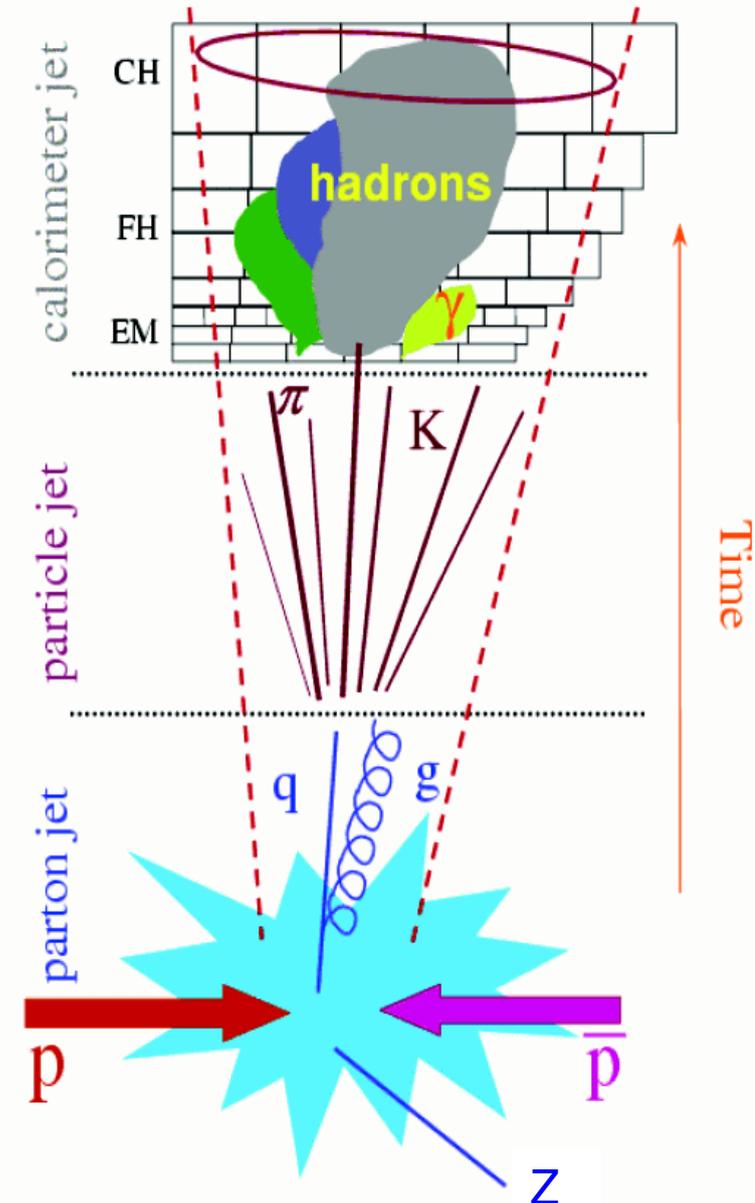
**Response:** fraction of total particle energy seen by the calorimeter

**Showering:** energy flow in and out of cone due to

- finite calorimeter tower size;
- magnetic field
- hadron shower size
- 1-5 % effect, function of  $\eta$

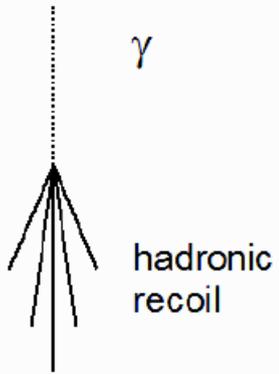
**Bias:** corrected using tuned MC

- negligible in this analysis



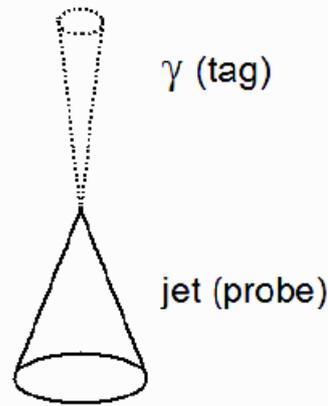
**Response calibration** based on momentum balance in photon + jet events

Particle Level



$$\vec{p}_{T,\gamma} + \vec{p}_{T,had} = \vec{0}$$

Detector Level



$$\vec{p}_{T,\gamma} + R_{had} \vec{p}_{T,had} = -\vec{E}_T$$

**Uncertainty dominated by:**

- photon ID at low pT
- EM scale (0.5 %),
- material effects (0.5 %)
- fragmentation & PDF uncertainty contribute at high pT

